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LARGE SPACE SYSTEM CONTROL TECHNOLOGY STATUS AND ACCOMPLISHMENTS

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LSST 1ST ANNUAL TECHNICAL REVIEW

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This is a report of technical progress made in FY'79 by JPL in the development of control technology for the LSST program. The report was presented at the first Annual LSST Program Technical Review held at Langley Research Center (LaRC) on November 7 and 8, 1979. Although the report was prepared by G. Rodriguez and G.L. Parker, the progress reflects the collective efforts of R.S. Edmunds, S.M. Gunter, J.N. Juang, E. Kan, Y.H. Lin, D.B. Schaechter, and C.J. Weeks of JPL.

The presentation includes topics which can be outlined as follows:

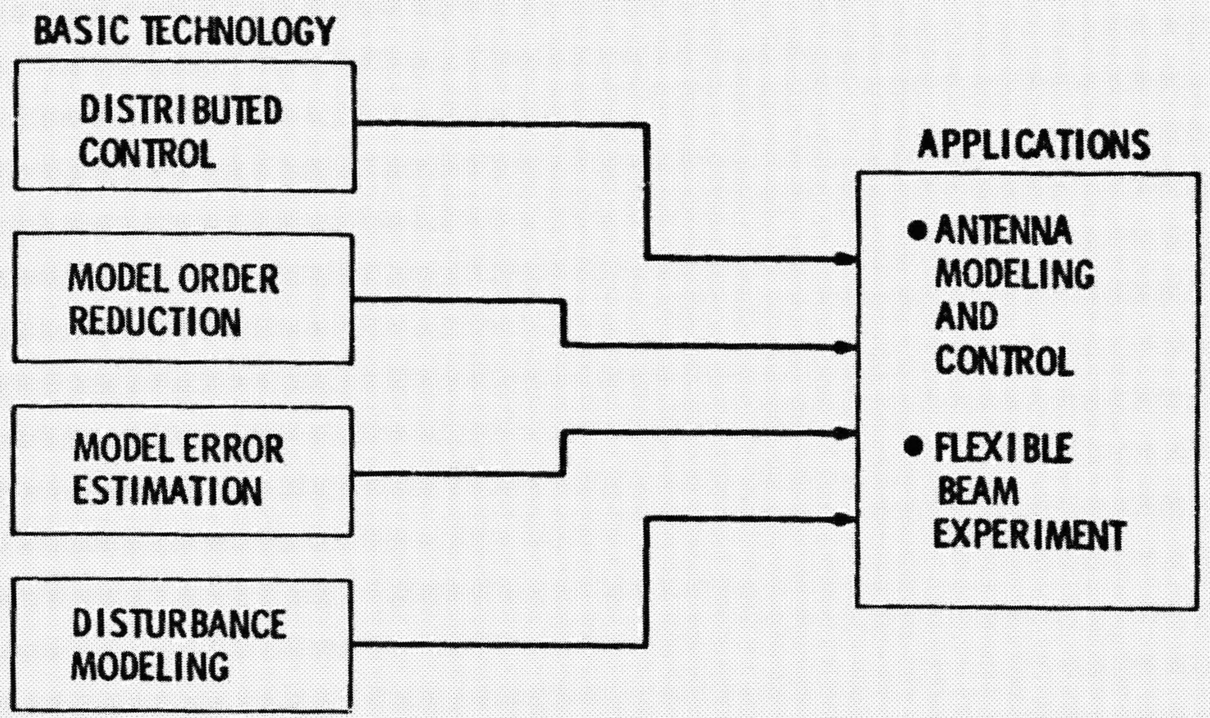
1. A summary of major objectives of FY'79 tasks
2. A description of major results and accomplishments
3. An outline of FY'80 planned developments
4. A current documentation list reflecting accomplishments to date.

CONTROL TASKS OVERVIEW

Basic technology developments were carried out in the areas of: 1) distributed control to achieve precision attitude and shape control; 2) model order reduction to find the best preflight dynamical models that retain the most significant vehicle dynamics in the controller design; 3) model error estimation to detect inevitable deficiencies in large structural dynamical models; and, 4) disturbance modeling to characterize the external environment for parabolic reflectors.

The applications for the basic technology are in the areas of antenna modeling and control and in the laboratory verification of selected concepts by means of a flexible-beam experiment demonstration.

CONTROL TASKS OVERVIEW



ACCOMPLISHMENTS

1) In the area of antenna modeling and control, preliminary structural models were defined for two representative parabolic reflectors. A control system design evolved for attitude control of the reflectors. The controller design was based on a lumped control concept where the control hardware (sensor and actuators) was mounted at the base of the antenna. 2) In the area of distributed control, static shape control techniques were worked out to establish a prescribed vehicle shape. The corresponding estimation process for determination of vehicle shape from selected sensor measurements was also developed. 3) A model order reduction study was conducted at Purdue University to find the best preflight dynamical models for on-board controller design. The objective of the study was to investigate (and initiate solution of) the problems caused by truncation of the vehicle dynamics required to minimize on-board computations. 4) Estimator designs were developed for on-board detection of large structure model errors. The model error estimators are a natural evolution of state estimation designs crucial to the success of recent JPL spacecraft. They would also constitute a foundation for development and eventual implementation of adaptive estimator concepts. 5) A study was conducted under contract to Lockheed for disturbance modeling of a 100-m diameter antenna in order to study the control/environment interactions. 6) An experimental (flexible-beam) facility was designed for verification of selected distributed control concepts.

ACCOMPLISHMENTS

- DEVELOPED PRELIMINARY STRUCTURAL MODELS AND CONTROL SYSTEM DESIGNS FOR ATTITUDE CONTROL OF PARABOLIC REFLECTORS
- DEVELOPED STATIC SHAPE AND MODAL TECHNIQUES FOR DISTRIBUTED CONTROL OF LARGE SPACE SYSTEMS
- CARRIED OUT A MODEL ORDER REDUCTION STUDY TO FIND THE BEST PRE-FLIGHT DYNAMICAL MODELS FOR CONTROL SYSTEM DESIGN
- DESIGNED MODEL ERROR ESTIMATORS FOR ONBOARD DETECTION OF INEVITABLE DEFICIENCIES IN LARGE STRUCTURE DYNAMICAL MODELS
- DEVELOPED DISTURBANCE MODELS OF A 100-m PARABOLIC REFLECTOR IN LOW-EARTH ORBIT TO STUDY CONTROL/ENVIRONMENT INTERACTIONS
- DESIGNED EXPERIMENTAL FACILITY FOR VERIFICATION OF SELECTED DISTRIBUTED CONTROL CONCEPTS

ANTENNA CONTROL

SUMMARY OF RESULTS

Finite-element models were developed by D.T. DesForges at JPL consistent with two antennas: a 30-m precision deployable design and a 100-m mesh deployable concept. Attitude and surface accuracy definitions were established in terms of structural data in order to allow computation of control performance. Preliminary control designs were developed based on a lumped control concept. Initial performance assessments based on the lumped control concept indicate that a more detailed model is required in order to determine if accuracy requirements can be satisfied with this concept. An assessment of the need for active surface control will be under investigation in FY'80. The disturbance modeling results will provide a tool for assessing the effects of dynamic external environment on the control performance.

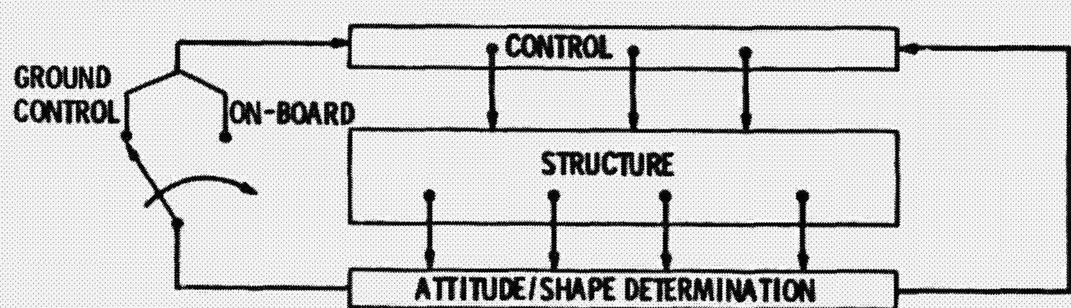
ANTENNA CONTROL SUMMARY OF RESULTS

- FINITE-ELEMENT AND MODAL MODELS OBTAINED FOR PARABOLIC REFLECTORS
    - 30m PRECISION DEPLOYABLE
    - 100m MESH-DEPLOYABLE
- ATTITUDE AND SURFACE ACCURACY DEFINITIONS ESTABLISHED IN TERMS OF STRUCTURAL DATA
- PRELIMINARY CONTROL DESIGN AND PERFORMANCE RESULTS DEVELOPED
- DISTURBANCE MODELING STUDY INITIATED

DISTRIBUTED CONTROL CONCEPTS

A distributed control system configuration is illustrated in the figure. In such a control system, sensor measurements of the vehicle deflections are processed by an on-board (possibly decentralized) computer that transmits commands to actuators in order to provide stability and control of the vehicle dynamics. A full-blown closed-loop distributed system as displayed in the figure may be required only in the most demanding applications. However, distributed estimation will be required in most large structures (even the earliest shuttle-based experiment) in order to establish the actual inflight dynamics and control/structure interactions. Consequently, an area of intensive study at JPL is that of estimation for distributed systems and its application to large structure control. The estimators detect both the quasi-static vehicle motions and the dynamics of the structure vibrational modes.

DISTRIBUTED CONTROL CONCEPTS



- DISTRIBUTED CONTROL OF LARGE FLEXIBLE STRUCTURES INVOLVES MULTI-STATION SENSING, ACTUATION AND CORRECTION TO MAINTAIN SHAPE
- SHAPE DETERMINATION AND ADJUSTMENT BASED ON GROUND COMMAND REQUIRED IN MOST APPLICATIONS
- ON-BOARD CLOSED-LOOP SYSTEM REQUIRED TO ACHIEVE HIGH PRECISION SURFACE ACCURACY

DISTRIBUTED CONTROL

SUMMARY OF RESULTS TO DATE

1) There are three fundamental options for distributed control system design models: partial differential equations, finite-element and modal models. There are substantial differences in the control systems resulting from these three approaches. The partial differential equation approach is very useful for early control concept design because it can be obtained without a full-blown analysis of the vehicle dynamics. Consequently, such continuum models can be used to study control-related problems that may otherwise be masked by model complexities. The modal approach has the advantage that it retains the physical insight gained by studying the vehicle dynamics in terms of the natural modes of the system. The finite-element models lead to localized controllers where each actuator command depends only on adjoining sensor measurements. An evaluation of each of these approaches is currently under investigation. 2) A fundamental problem in large structure control is that of achieving a prescribed vehicle shape and of establishing shape knowledge based on measurements of the structural deflections. Problems formulated and solved in FY'79 are those of static shape determination and control. In the area of shape estimation, the technique used to achieve the shape reconstruction process is based on the principle of least-squares that minimizes the errors in the system model. A general solution for estimation of distributed parameter systems has been worked out and applied to a flexible-beam structural model. The corresponding solutions for static shape control have also been established. 3) In the area of dynamic shape determination and control, analytical criteria for sensor/actuator placement have been established and applied in the estimation of a single large structure vibrational model.

DISTRIBUTED CONTROL
SUMMARY OF RESULTS TO DATE

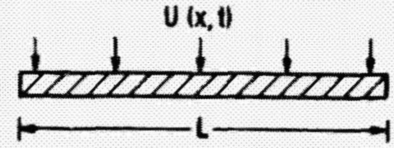
- MODELING OPTIONS FOR CONTROL SYSTEM DESIGN
  - CONTROL AND ESTIMATION SCHEMES DEVELOPED BASED ON CONTINUOUS MODELS
  - MODAL CONTROL AND SPILLOVER INVESTIGATED
  - → LOCAL DISTRIBUTED CONTROL SYSTEMS DESIGNED FOR BEAM-LIKE STRUCTURES
- → STATIC SHAPE DETERMINATION AND CONTROL
  - LEAST-SQUARES SOLUTION ESTABLISHED
  - APPLICATION TO FLEXIBLE BEAM-LIKE STRUCTURE
  - FEEDBACK SOLUTIONS FOR STATIC SHAPE CONTROL
- DYNAMIC SHAPE DETERMINATION/ESTIMATION
  - → SENSOR/ACTUATOR PLACEMENT
  - ESTIMATION OF A SINGLE LARGE STRUCTURE VIBRATIONAL MODE

LOCAL CONTROL BASED ON FINITE ELEMENTS

Finite-element analysis is currently the most widely used technique to study the dynamics of flexible space structures. The finite-element method is so versatile and generally applicable that general purpose computer program packages (e.g. NASTRAN, SPAR, etc.) based on this method solve an almost limitless variety of problems in structural mechanics. A finite-element model for an undamped flexible structure typically results in a set of dynamic equations of the form shown in the viewgraph. This set of equations is normally used to set up an algebraic eigenvalue problem whose solution produces the natural frequencies and modes of the vehicle. The resulting eigenvalue problem can be solved very efficiently by making optimum use of the inherent sparsity and bandedness of the matrices in the foregoing formulation.

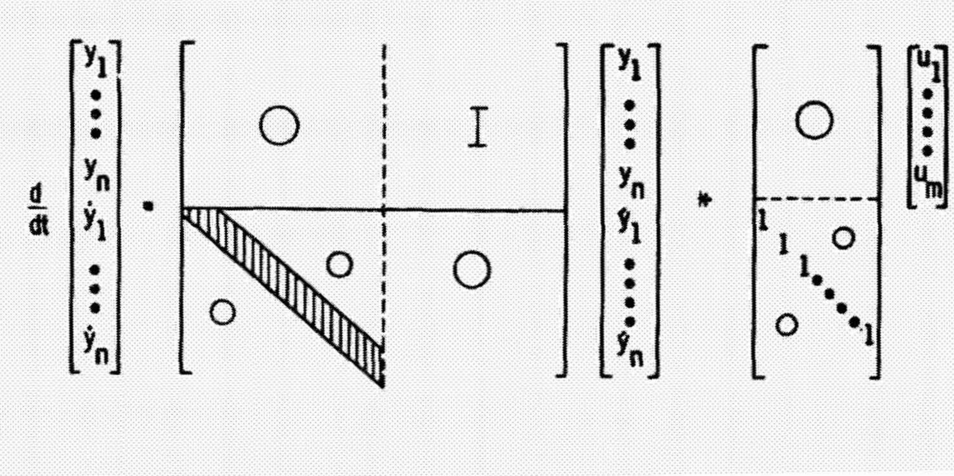
A uniquely original idea introduced by D.B. Schaechter at JPL (see Ref. 1) is to make similar use of the highly structured format of the mass/stiffness matrices in the finite-element formulation in order to obtain distributed control designs. This design approach leads to localized estimators/controllers where control inputs at any given location are based only on adjoining sensor measurements. This approach takes full advantage of matrix sparsity in order to minimize storage requirements and on-board computations. The local control scheme has proved to be a most promising method for control system design when compared with various other schemes (e.g. modal control) in a representative simplified structure (Ref. 2).

LOCAL CONTROL BASED ON FINITE ELEMENTS



$$\rho \frac{\partial^2 y}{\partial t^2} + EI \frac{\partial^4 y}{\partial x^4} = U(x,t)$$

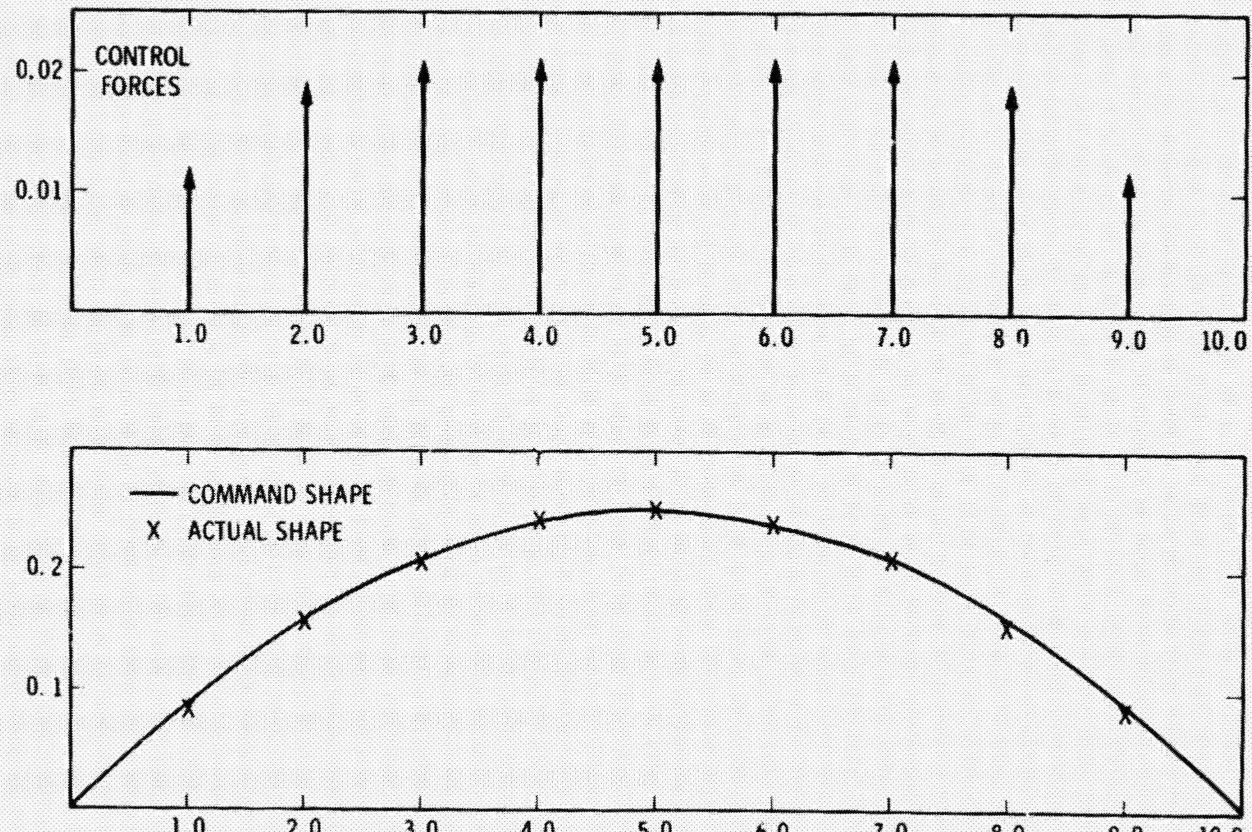
MODEL



STATIC SHAPE CONTROL

The viewgraph illustrates basic developments in the area of static shape control where the objective is to achieve a prescribed vehicle shape. The results obtained (Ref. 3) are sufficiently general to be applicable to a large class of space systems. The figure shows only the application to a one-dimensional elastic structure. Two plots are displayed in the figure corresponding respectively to deflection and control inputs. The prescribed or commanded shape is a parabola. The objective of the control scheme is to bring the actual structural shape to a configuration that best approximates in a least-squares sense the specified parabola. The resulting control forces that cause the required vehicle deflection are shown in the upper plot in the viewgraph. Current efforts are directed at the extension of the foregoing results to two dimensional configurations.

STATIC SHAPE CONTROL



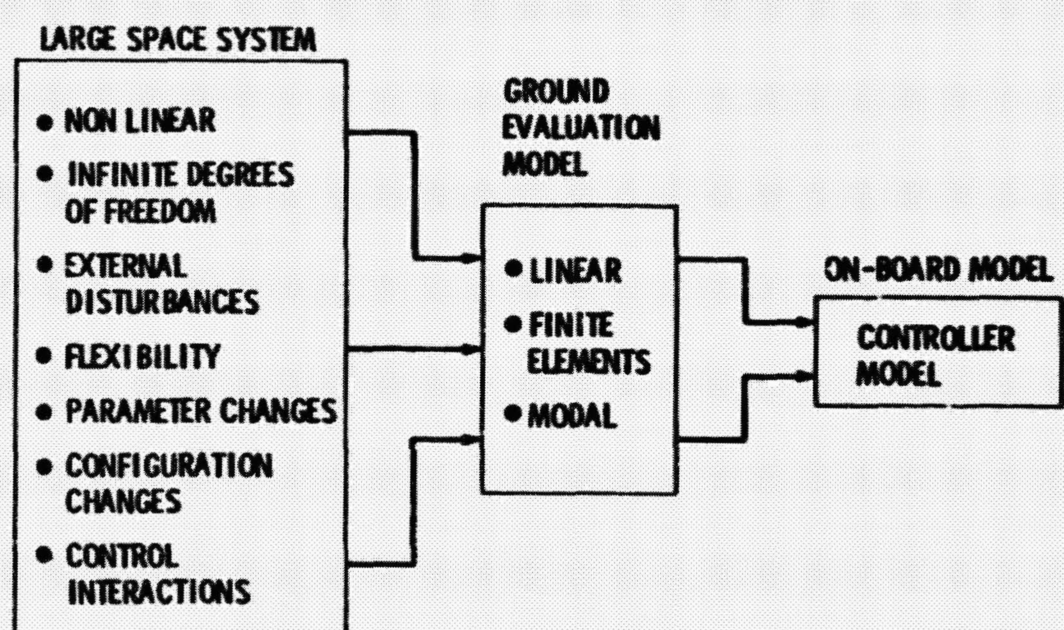
MODEL ORDER REDUCTION

PROBLEM STATEMENT

Modeling for controller design is widely recognized as a major and as yet unsolved problem in achieving precision attitude and shape control. Due to size and flexibility (and the resulting limitations of pre-flight model verifications), a great potential exists for errors in the dynamical models for large structures. In addition, the models used for controller design will be at best reduced-order representations of the structure because 1) large structures are infinite-dimensional systems that cannot be characterized fully by any finite-dimensional model and 2) model order reduction is required to minimize on-board computations.

The modeling process consists of a number of model order reduction stages. The actual large space system corresponding to the left block in the viewgraph is characterized by an infinite number of dimensions and uncertain physical effects. An evaluation model is usually developed based on linearized equations and on a finite-element or modal description of the structure. This evaluation model is used for verification of control system design. In order to obtain the controller model, a further stage of model reduction has to be carried out.

MODEL ORDER REDUCTION PROBLEM STATEMENT



- LARGE STRUCTURES ARE INFINITE-DIMENSIONAL SYSTEMS THAT CANNOT BE COMPLETELY MODELED
- MODEL ORDER REDUCTION IS REQUIRED TO MINIMIZE ON-BOARD COMPUTATIONS AND IMPLEMENTATION COMPLEXITY

The model order reduction study was carried out under contract to Purdue University. The study was initiated by first selecting a generic large structure to illustrate the basic technology developments in model reduction. A number of reduction methods were investigated and a comparative evaluation of selected methods carried out. The method chosen for further investigation is a so-called modal cost analysis technique that tailors reduced-order models to the actual control inputs. Current efforts are directed toward application of the method of modal cost analysis to the generic large structure. A more detailed description of the foregoing results is contained in a subsequent presentation by R.E. Skelton of Purdue University.

MODEL ORDER REDUCTION

- DEVELOP MODEL ORDER REDUCTION METHODS FOR REDUCED-ORDER CONTROLLER DESIGN
- STUDY METHODS FOR MODELING DYNAMICAL SYSTEMS AND ESTABLISH MODEL SELECTION CRITERIA TO CHOOSE TYPES OF MODES TO RETAIN IN THE CONTROLLER DESIGN
- DEVELOP STABILITY, CONTROLLABILITY AND OBSERVABILITY PROPERTIES OF DYNAMICAL SYSTEMS DESCRIBED BY LINEAR MATRIX SECOND-ORDER SYSTEMS
- SELECT A GENERIC SPACE STRUCTURE TO BE USED FOR NUMERICAL ILLUSTRATION
- SUMMARIZE SELECTED MODEL REDUCTION METHODS AND CLASSIFY METHODS ACCORDING TO THEIR SUITABILITY FOR THE GENERIC LARGE STRUCTURE
- INVESTIGATE THE METHOD OF ITERACTIVE MODEL REDUCTION WITH COST-SENSITIVE FORCED MODES TO TAILOR REDUCED-ORDER MODELS TO OPTIMAL CONTROL INPUTS
- SPECIALIZE THE THEORY OF COST-SENSITIVE MODEL REDUCTION METHODS TO LINEAR MATRIX - SECOND-ORDER SYSTEMS
- PERFORM COMPARATIVE EVALUATION OF SELECTED MODEL ORDER REDUCTION METHODS TO GENERIC LARGE STRUCTURE

Inflight estimation of large structure model errors will have to be carried out in order to detect inevitable deficiencies in large structure estimator models. The models used for controller design will be at best reduced-order representations of the structure because 1) large structures are infinite-dimensional systems that cannot be characterized fully by any finite-dimensional model and, 2) model order reduction is required to minimize on-board computations. Inherent in a reduced-order model are so-called model errors due to four major sources: external disturbances, parameter uncertainties, neglected nonlinearities and truncated dynamics. A formulation for on-board model error estimation based on the principle of least-squares is contained in Ref. 4. The technology base used as foundation to carry out the developments consisted of 1) modeling for dynamics and control of flexible multibody systems, and 2) state estimators critical to recent JPL spacecraft designs. This technology has been found to be essential to all highly flexible and interactive spacecraft. Continued intensive developments in this area could provide an opportunity to have a significant impact on the Galileo attitude estimator design.

The process of model error estimation is illustrated in the next three viewgraphs.

MODEL ERROR ESTIMATION

PURPOSE

- DESIGN ESTIMATORS CAPABLE OF ON-BOARD DETECTION OF INEVITABLE DEFICIENCIES IN LARGE STRUCTURE DYNAMICAL MODELS

EXISTING TECHNOLOGY BASE

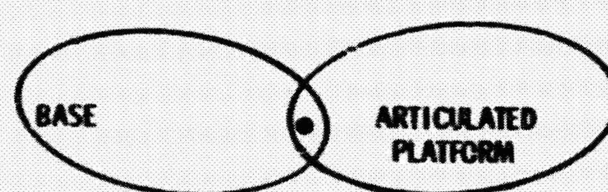
- STATE ESTIMATION TECHNOLOGY CRITICAL TO VIKING, VOYAGER, AND GALILEO CONTROL PERFORMANCE
- TECHNOLOGY IS ESSENTIAL FOR HIGHLY FLEXIBLE AND INTERACTIVE SPACECRAFT
- CONTINUED INTENSIVE DEVELOPMENTS WILL PROVIDE OPPORTUNITY TO IMPACT GALILEO ATTITUDE ESTIMATOR DESIGN

ILLUSTRATION OF MODEL ERROR ESTIMATION

A representative vehicle is formed by two rigid elements joined at a single-degree-of-freedom hinge. A perfectly acceptable reduced-order model for this configuration would be the linear single-axis equations for rotational motion of a rigid body. In fact, such an approximation was used in the flight-tested Voyager estimator design. However, the selection of this single-body model for the two-element configuration implies the unavoidable presence of model errors in the characterization of the vehicle dynamics. The model errors are due to four major sources as illustrated in the viewgraph. The model errors can however be lumped and represented in the dynamical model as the variables u and n appearing as forcing terms in the model equations. The objective of model error estimation is to estimate these terms in addition to providing estimates of the state (i.e., angular position and velocity) of the system. The data required to achieve the estimation process consists of measurements of the angular orientation of the vehicle with respect to a celestial reference.

ILLUSTRATION OF MODEL ERROR ESTIMATION

SYSTEM - TWO-BODY



REDUCED-ORDER MODEL

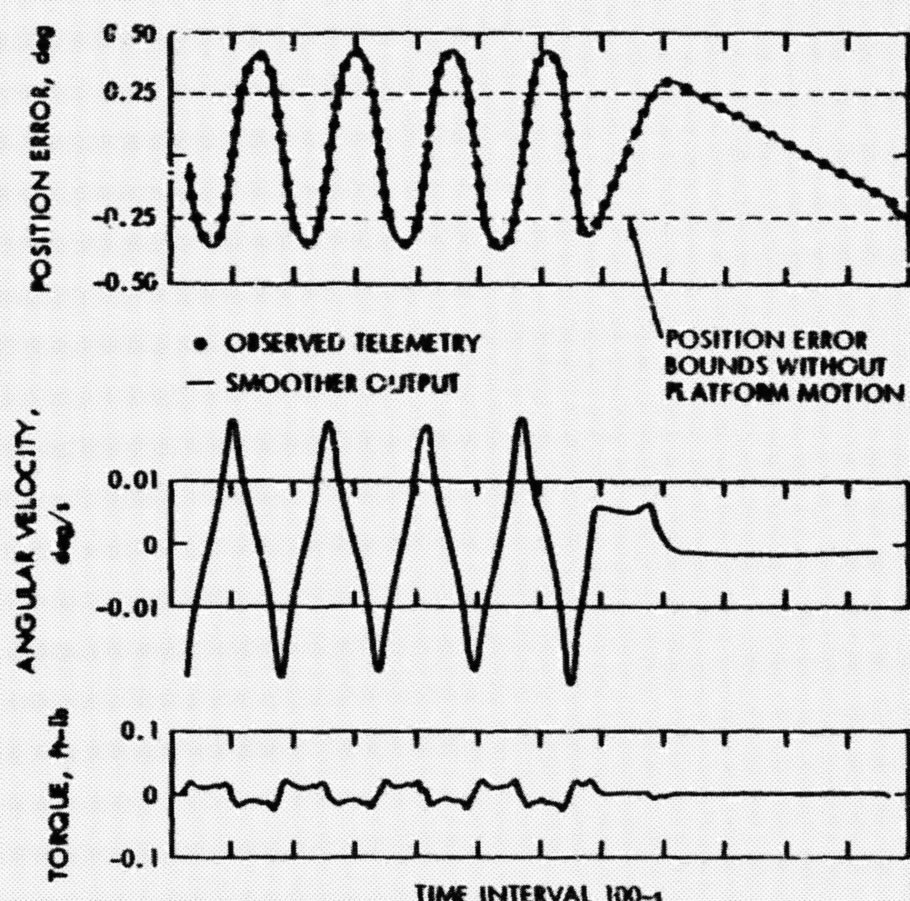
$\dot{\theta} = \omega$	KINEMATICS
$\dot{\omega} = u$	DYNAMICS
$y = \theta + n$	OBSERVATION

MODEL ERRORS

$$\begin{bmatrix} u \\ n \end{bmatrix} = \text{EXTERNAL DISTURBANCES} + \text{TRUNCATED DYNAMICS} + \text{NEGLECTED NONLINEARITIES} + \text{PARAMETER UNCERTAINTIES}$$

Estimation of the inflight dynamics of a flexible spacecraft is shown in the figure. The plots correspond respectively to angular position, velocity and estimated model error as functions of time. The available measurements to achieve the required state-variable reconstruction consist of samples of the angular position at the discrete instants in time (see top plot). The data used in the plots corresponds to an actual JPL spacecraft formed by a central rigid bus and an articulated subassembly. The spacecraft dynamics can therefore be represented by the two-element configuration described previously in this presentation. The estimation process was however based on a single-rigid-body model. Consequently, the truncated subassembly motion is reflected as equivalent torques (model errors) in the reduced-order model. The model error estimates shown in the bottom plot very clearly indicate the presence of the truncated motion. Such a model error estimation concept can therefore be used to detect the presence of unmodeled vehicle dynamics. The application of this approach to distributed systems is currently under investigation. A summary of current results is reported in Ref. 4.

INFLIGHT MODEL ERROR ESTIMATION



FLEXIBLE BEAM CONTROL OBJECTIVES

The objectives of hardware demonstration using a flexible beam as the "large space structure" (LSS) are to demonstrate active static and dynamic shape control in a real or near-real environment, on which basis our mathematical analysis and simulation are to be verified. This demonstration also provides a test-bed to further development on mechanization and on sensors and actuators.

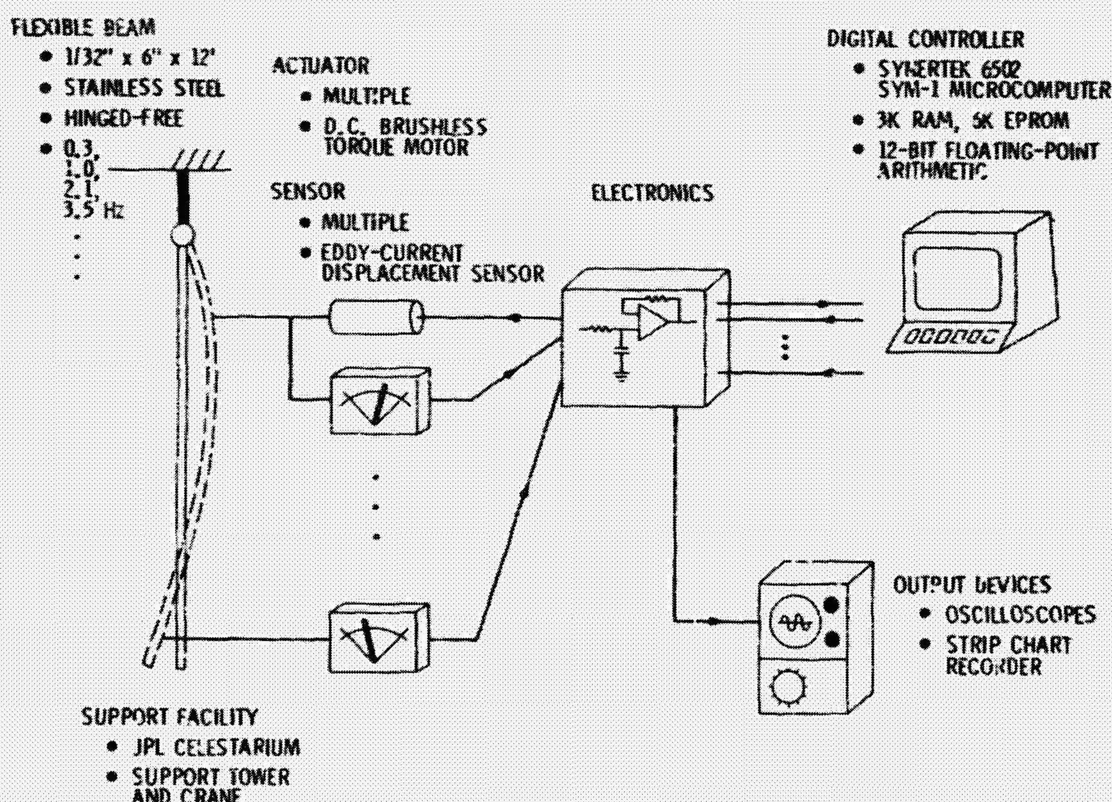
Not only will the demonstration validate the theoretical analysis but it will bring insight into possible problems in integration and mechanization of the control of LSS. Model inefficiencies, spillover of control or observation, real-world computation limitation and other deficiencies could be detected that will shed light to better and more robust control law and system model design. Such a scaled model demonstration is deemed indispensible as a precursor to full-scaled space demonstration.

LSS FLEXIBLE BEAM CONTROL DEMONSTRATION OBJECTIVES

- TO DEMONSTRATE ACTIVE STATIC SHAPE CONTROL
- TO DEMONSTRATE ACTIVE DYNAMIC SHAPE CONTROL, i.e., DISTURBANCE DAMPING AND SHAPE CONTROL
- TO FURTHER DEVELOP AND TO PROVIDE TEST-BED FOR TESTING SENSORS AND ACTUATORS
- TO AUGMENT AND TO VERIFY MATHEMATICAL ANALYSIS AND SIMULATION SOLUTIONS UNDER REAL OR NEAR-REAL ENVIRONMENT

There are four major categories in the instrumentation of the beam control demonstration: (1) flexible beam, (2) actuator, sensor and electronics, (3) digital controller (data processor), and (4) support facilities. The 1/32" x 6" x 12' beam is made of stainless steel. It is hung vertically, hinged at the top and free at the bottom. It has a fundamental frequency, i.e. pendulum rigid-body mode, at 0.3 Hz. Multiple actuators and sensors, with variable location along the beam, are planned. Current configuration has 3 actuators and 4 sensors. Static shape control and multiple mode (≤8) dynamic control can be implemented. The actuators and sensors are all off-the-shelf items, the former being d.c. brushless torque motors and the latter eddy current displacement sensors. FY'79 accomplishments include the establishment of the facility; procurement, fabrication and integration of the hardware; software development on the microcomputer to perform static and dynamic shape control; and preliminary experimentation of the control of the beam. With the present set up, various control laws can be tested, such as full-state optimal control, local-state control, and adaptive control. Optimal combination and placement of actuators and sensors can be experimented. Model order reduction and estimation can be investigated using the present facility.

LSS FLEXIBLE BEAM CONTROL DEMONSTRATION INSTRUMENTATION



FY'80 PLANNED DEVELOPMENTS

The direction for the FY'80 JPL LSST Controls Program is to characterize, define and initiate solution of the control problems for specific platforms (small science platforms and large multiple payload platforms) and for parabolic reflectors.

The specific tasks to be implemented are tabulated below:

Control of Science Application Platforms

Control of Large Multiple-Payload Platforms

Control of Large Parabolic Reflectors

Analysis and Simulation

Justification of these tasks results from the fact that it is necessary to investigate in detail the performance and stability of specific platforms and antennas in order to achieve an integrated structure and control design approach. The control/structure/performance interaction must be defined and understood in order to develop technology to assure control mechanizations which will accommodate these systems. The specific output of these tasks will be to define and illustrate parametrically control problems and to identify the technology developments necessary to enable subsequent missions.

FY 80 PLANNED DEVELOPMENTS

- PROVIDE A QUALITATIVE DEFINITION OF CONTROL PROBLEMS FOR A SCIENCE APPLICATIONS PLATFORM, A MULTIPLE PAYLOAD PLATFORM AND A PARABOLIC REFLECTOR
- CARRY OUT A COMPARATIVE EVALUATION BETWEEN DISTRIBUTED AND LUMPED CONTROL CONCEPTS
- CARRY OUT PARAMETRIC CONTROL PERFORMANCE STUDIES FOR PLATFORMS AND PARABOLIC REFLECTORS
- PERFORM A MODEL ORDER REDUCTION STUDY TO IDENTIFY AND ILLUSTRATE PARAMETRICALLY CONTROL PROBLEMS CAUSED BY INEVITABLE MODEL ERRORS
- INVESTIGATE PLATFORM CONTROL PROBLEMS CAUSED BY SENSOR AND ACTUATOR SEPARATION BY FLEXIBLE STRUCTURAL ELEMENTS

DOCUMENTATION

Most of the results obtained to date in the JPL control technology development program have been documented. A total of 6 technical conference papers have been presented. The Purdue contract has produced 5 reports in the area of model order reduction. A number of internal JPL reports provide a less formal but nonetheless substantial record of accomplishments to date. This documentation is available from JPL upon request.

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